A COMPARATIVE STUDY OF MEASURING DEVICES USED DURING SPACE SHUTTLE PROCESSING FOR INSIDE DIAMETERS

by

Antonio Rodriguez

A Technical Management Capstone Project
Submitted to the Extended Campus
in Partial Fulfillment of the Requirements of the Degree of
Master of Science in Technical Management

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This Technical Management Capstone Project
was prepared under the direction of the candidate's Research Committee Member,
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ABSTRACT

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Institution: Embry-Riddle Aeronautical University

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During Space Shuttle processing, discrepancies between vehicle dimensions and per print dimensions determine if a part should be refurbished, replaced or accepted "as-is." The engineer's job is to address each discrepancy by choosing the most accurate procedure and tool available, sometimes with up to ten thousands of an inch tolerance. Four methods of measurement are commonly used at the Kennedy Space Center: 1) caliper, 2) mold impressions, 3) optical comparator, 4) dial bore gage. During a problem report evaluation, uncertainty arose between methods after measuring diameters with variations of up to 0.0004" inches. The results showed that computer based measuring devices are extremely accurate, but when human factor is involved in determining points of reference, the results may vary widely compared to more traditional methods.

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CHAPTER I

INTRODUCTION

Background of the Problem

During Space Shuttle processing, United Space Alliance (USA) has the responsibility of updating systems required by the National Aeronautics and Space Administration (NASA), inspecting flight hardware periodically and repairing discrepancies generated from flight hardware inspections. In many situations, discrepancies are written against parts that need to be compared against drawing tolerances.

During the 2002-2004 Orbiter Maintenance Down Period (OMDP), the Body Flap (BF) of the Space Shuttle "Discovery" was removed from its four rotary actuators located in the AFT fuselage, which are controlled by the flight control system and the hydraulically actuated rotary actuators (NSTS, 1998). Each actuator contains a number of attach points accompanied for alignment bushings. Quality inspectors noted that most of the alignment bushings had discrepancies in their radius after Body Flap removal.

To solve this problem, engineering was authorized to measure each one of the alignment bushing's inside diameter (I.D) to see if they can be accepted "as-is", or if they need to be repaired or replaced. The technician obtained the I.Ds for all bushings by taking sets of dental mold impressions (Reprosil) for each bushing. The molds were later read using an optical comparator (see Figure 1). Due to unexpected results from the molds and because of the bushing's tight tolerances of +0.0000/-0.0005 inches per drawing, a second set of measurements was obtained; this time using a dial bore gage (see Figure 2).

Results from the two methods (molds and dial bore gage) were different from each other, but reasonably close to the expected nominal value. Therefore, most of the bushings were accepted “as-is”.

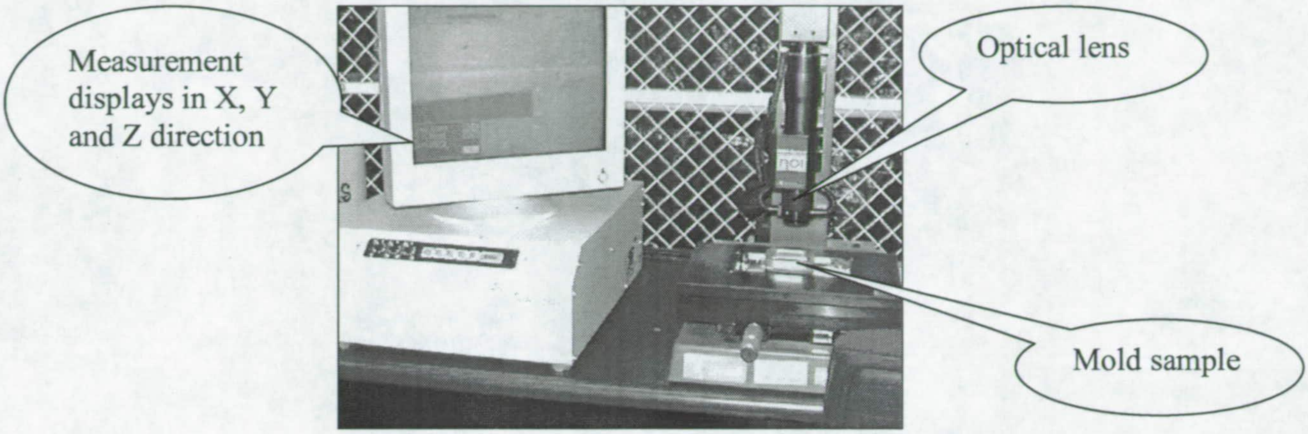

Figure 1. Optical comparator.

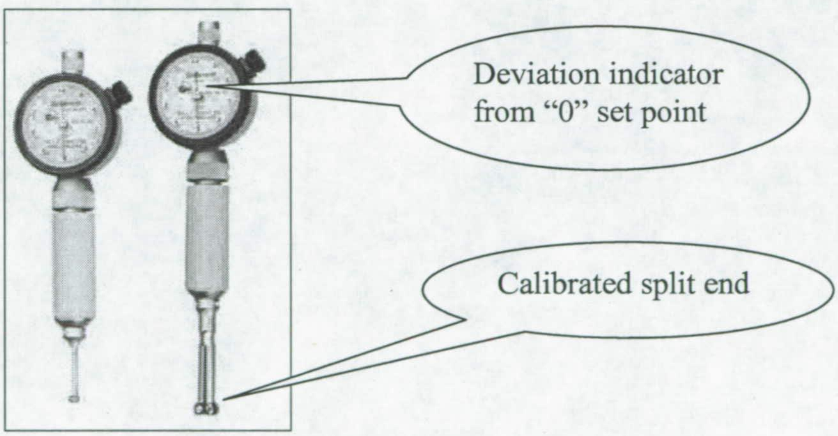

Figure 2. Dial bore gage.

After seeing the results from both measuring methods (molds and dial bore gage), uncertainty arose between engineers, who determined that the difference in results could be caused by human error or because some measuring methods are not accurate enough

to measure diameters with tight tolerances of +0.0000/-0.0005 inches. The actual bushing per print dimensions is I.D = $0.8750^{+.0000}_{-.0005}$ inches.

Statement of the Problem

Measuring devices used at the KSC depend greatly on the part's size, its assembly and its location. The most common measuring devices include mold impressions, optical comparator, calipers and dial bore gages. All four methods are practically accurate when measuring I.Ds, but some became questionable when the part to be measured allowed tolerances of only +0.0000/-0.0005 inches.

Assumptions

I.D measurements from all five methods are expected to be performed by professional quality inspectors that read and record data to their best approach.

The sample (bushing) was expected to be relatively round without noticeable elongation because it came new from logistics.

Expansion or contraction of the sample's material and/or measuring devices due to change in temperature (handling, room temperature, etc) was insignificant because of size of the sample. All measurements were performed under the same conditions.

All four measuring devices had at least ten thousandths of an inch accuracy, which is adequate resolution to detect small changes when measuring the bushing diameter.

Limitations

Three measuring devices, caliper, dial bore gage and especially the optical comparator were used for a limited time due that this project was not sponsored by USA.

Quality inspectors' time used to read the diameters was a courtesy.

Dental Mold Impressions (Reprosil) is an expensive material. USA logistics donated just enough mold impressions material to fulfill one run of this project.

Measuring test was not randomly controlled.

A typical gage study looks at both repeatability and reproducibility. Since the same person is not always going to take the measurements, it is impractical to do reproducibility at this point.

Delimitations

Even though the researcher could mark the point of reference on the mold impression or on the part itself, nothing guaranteed that the quality technician read the diameter using exactly the same point of reference.

Definition of Terms

Caliper – Mechanical device used to directly measure inside, outside or depth dimensions.

CSR – Special certification required for quality technicians to use the optical comparator and obtain official measurements.

Dial bore gage – Mechanical device used to read variations from a known dimension or standard.

Human Error – Any mistake by someone directly involved with the utilization of measuring devices such as calipers, dial bore gages, etc.

Inside Diameter (I.D) – Smaller diameter of a bushing.

Mold impressions – Material used to obtain a replica to a 0.0002" tolerance when a part cannot be measured directly.

Optical comparator – Precision measuring system that maximizes small details to 20X, 30X, etc. Once points of reference are set, the computer takes the measurements.

Orbiter Maintenance Down Period – Two to two and a half years period where the orbiter is kept at KSC facilities for updates, re-furnish, inspections and general repairs.

Reprosil – Also known as dental mold impression.

United Space Alliance – A joint venture between The Boeing Company and Lockheed-Martin Company to fulfill the requirements of the Space Flight Operations Center.

WAD – Official document used at KSC where the dispositioner authorizes work.

Acronyms

BF	Body Flap
CSR	Certified Special Repair
I.D	Inside Diameter
INBD	Inboard
KSC	Kennedy Space Center
NASA	National Aeronautic and Space Administration
OMDP	Orbiter Maintenance Down Period
R&D	Research and Development
SFOC	Space Flight Operations Center
USA	United Space Alliance
WAD	Work Authorization Document

CHAPTER II

REVIEW OF RELEVANT LITERATURE AND RESEARCH

Human Error

Based on the definition by Holman (1994), *Experimental Methods for Engineers*, Chapter 3.2, there are causes and types of experimental errors:

If the experimenter knew what the error was, he or she would correct it and it would no longer be an error. In other words, the real errors in experimental data are those factors that are always vague to some extent and carry some amount of uncertainty. The engineer's task is to determine just how much uncertainty there may be in a particular observation and to devise a consistent way of specifying the uncertainty in analytical form (Cooper, 2003).

Analysis of data determines errors, precision, and general validity of experimental methods. In general, errors are present in all measurements regardless the care of the experimenter. In this case, the engineer's job is to reduce the errors to a minimum when measuring I.Ds of round parts during the Space Shuttle processing.

No measurement can yield one absolutely true value. Rather, the best one can hope for is a best estimate. In addition, one can collect enough information to tell how sure one can be of the best estimate.

Measurement and Uncertainty

Experimental data collected in a given experiment are frequently normally distributed around a mean value. Here, the example is a bushing, which is measured several times. Each time a data point is collected, the result is scored and the mean value and the deviation of the distribution are determined.

The Caliper

Based on Walker's (2000) book *Machining Fundamentals*, caliper, also known as, "Vernier" (see Figure 3) was the principle of measurement and was named for its inventor, Pierre Vernier, a French mathematician. The Vernier caliper can make accurate measurements to 1/10000" (0.0001").

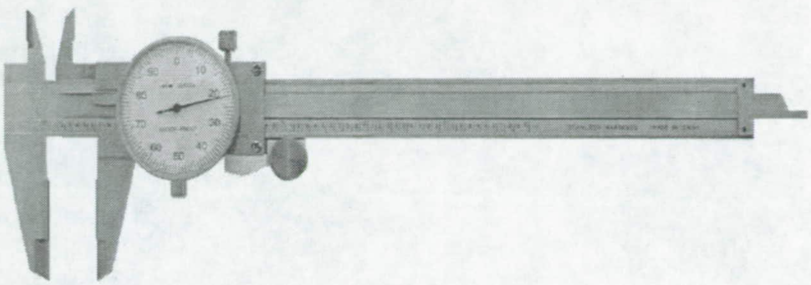

Figure 3. Caliper.

The design of the tool permits measurements to be made over a large range of sizes. It is manufactured as a standard item in 6", 12", 24", 36" and 48" lengths. The 6" and 12" sizes are most commonly used. Unlike the micrometer caliper, the Vernier caliper can be used for both inside and outside measurements.

Using the Caliper

As with any precision tool, a Vernier caliper must not be forced on the work. To use the Vernier Caliper, first slide the Vernier assembly until the jaws nearly contact the section being measured, then, lock the clamping screw in a way that the jaws contact the work firmly, but not tightly. Finally, remove the tool from the work and make the reading. For precise layout work, divider and trammel point settings are located on the outside measuring scale and on the slide assembly (Walker, 2000).

Digital Calipers

These direct-reading instruments resemble Vernier calipers. They can be used to make outside, inside and depth measurements (with the addition of a depth attachment). A lock permits the tool to be employed for repetitive measurements. The digital caliper used for this study showed the reading in the caliper's screen when the jaws were moved along the beam. Increments of 1/10000 or 0.0001" are shown on the caliper's screen. Some digital micrometers can read up to 0.00001" accuracy (Walker, 2000).

The Dial Bore Gage

There are two types of dial bore gages (indicators): balanced and continuous. Balanced indicators can take measurements on either side of a zero line. Continuous indicators read from "0" in a clockwise direction (see Figure 2).

For this study, the balanced dial bore gage was available. Knowing that the tool was calibrated, a round standard is utilized to zero out the indicator (note that the standard varies depending upon the diameter of the part to be measured). The split end is then introduced into the inside diameter (I.D) and the oscillation of the indicating needle from the zero is the value in the plus or negative side, which is subtracted from the standard diameter (Walker, 2000).

Optical Comparator

Based on information on optical comparators obtained from http://www.qualitydigest.com (Davis, 2001), the old adage "seeing is believing" is appropriate when referring to optical comparators. Because these measurement tools display a magnified image of a part, a tremendous amount of information about that part

can be gathered in a short time simply by looking at the image. Optical comparators are inspection machines that project magnified images of parts onto a glass screen using illumination sources, lenses and mirrors for the primary purpose of making 2-D measurements.

Dating back as far as calipers, optical comparators have been used for more than 50 years and remain a versatile and cost-effective technology for monitoring the processes and quality of a broad range of manufactured parts. Originating from static overhead projectors that displayed magnified images of screw threads onto a wall for manual measurement, optical comparators have evolved into full-featured machines that use modern mechanical, electrical and optical technology to minimize inspection time and maximize cost savings (see Figure 1).

Comparators Advantages

Optical comparators can provide more information than just simple dimensions. Length and width measurements can be quickly obtained from two separate measurements by using a micrometer. These superficial measurements, however, might not reveal burrs, scratches, indentations or undesirable chamfers. Such imperfections are best detected on a comparator. In addition, a comparator's screen can be simultaneously viewed by more than one person and provide a medium for discussion, just as a white board might facilitate a conference (Davis, 2001).

Another advantage of comparators is their ability to measure in 2-D space. Unlike micrometers and calipers, which measure one dimension at a time, comparators measure length and width simultaneously. To do this, the operator lines up the lower left-hand corner of the image with the screen centerline to establish a zero point, and then

checks the upper right-hand corner to get a simultaneous reading of both length and width. The straight-line distance from corner to corner can be obtained with a single keystroke (Davis, 2001).

Measuring Diameters

Optical comparators are used to measure manufactured parts in a wide range of industries around the world every day. Available with numerous features and options to suit many applications, comparators can be used throughout a factory, including incoming inspection areas, R&D (Research and Development) labs, machine shops, assembly and production floors, and final inspection areas. Their versatility, range of capabilities and return on investment make comparators indispensable and integral to any quality plan.

Constructed points, gage points or gage lines that appear on part drawings can be established quickly on optical comparators, making relative measurements from these "points in space" easy to perform (Length and Distance, 2004). To measure a part, for example, the right side of the part is aligned with the vertical centerline, and a zero position is set. The part is moved to the right by the nominal depth given on the drawing. A diameter is then measured at this depth by moving the part vertically and measuring points on each angled surface.

Mold Impressions

Among engineers in the USA Structures department at the KSC, mold impressions are the most common technique to measure diameters when the circumference is elongated and hard to reach with conventional measuring tools like calipers. Mold impressions allow engineers to obtain measurements within +/- 0.0002

inches. Molds are very trusted in essence because they are read in a computer based optical comparator (see Figure 1).

Figure 4. Mold impression material (Reprosil) and sample.

Since the introduction of the impression technique in the Space Shuttle processing, exact working models allowed engineers to measure areas where limited access could not allow the use of more conventional measuring tools. In addition, fine details such as corrosion depth, cracks, gauges and elongations can be easily reproduced using this technique.

The mold impression material comes in a box with a syringe like applicator. The applicator mixes up two cylinders of medium consistency material and is pushed out by a gun applicator. Material is poured inside the hole (I.Ds) or in a small container where the bushing is placed (O.Ds). After five minutes, the mold material is cured and can be taken out from the bushing due to its elastic consistency. Excess mold impression material

cannot be re-used once air has been introduced inside the application cylinders. Bulk excess cured material can be trimmed with a knife or scissors to facilitate reposition on the optical comparator table later (see Figure 1).

Summary

This chapter reviews literature identifying the most accurate techniques to measure diameters during the Space Shuttle processing when diameters have relatively round contours and have easy accessibility. Measuring devices and techniques were described including their application, accuracy and basic reading.

Statement of the Hypothesis

The hypothesis for this study was based on three situations experienced during the Space Shuttle processing. In all three situations, a part needed to be measured to the ten thousandth of an inch accuracy to determine if it required repair or was acceptable as is. In one particular situation, for example, all bushings for the Body Flap attach points were measured using molds technique because it is believed to have an accuracy of up to 0.0002". Measurements obtained from all eight bushings were very different from each other and were also outside the per print parameters. Second and third sets of measurements were obtained using a micrometer and a caliper respectively showing that these two traditional devices were closer to the expected diameters compared to the molds.

Mold impressions technique truly gives up to 0.0002" accuracy, but such accuracy was compromised by human error when molds were read in an optical comparator. The researcher's hypothesis is that mold impressions technique are useful when traditional measuring devices cannot reach a diameter (caliper, micrometer, etc)

and/or the circumference is elongated. Otherwise, mold impressions technique could compromise the results by unconsciously introduce human error.

Rejecting the null hypothesis meant that dental mold techniques to measure round samples with easy access is more accurate than the caliper, dial bore gage, micrometer and optical techniques.

The following hypothesis was based on a bushing diameter with relatively round contour and easy access:

H_o: dental mold technique is not as accurate or only as accurate as the more traditional techniques such as caliper, micrometer, dial bore gage and optical comparator.

H_a: dental mold technique is more accurate than the more traditional techniques such as caliper, micrometer, dial bore gage and optical comparator.

CHAPTER III

RESEARCH METHODS

The research methodology used for this project was causal-comparative. The causal part came into play in defining techniques and devices that can measure diameters with ten thousand of an inch accuracy. The comparative assessment was made when data from each measuring device was compared against each other and against a nominal value per print. This process ultimately had the end goal in mind of determining the acceptance or rejection of the hypothesis statement.

Research Design

This study developed a process for which a quality technician measured the inner diameter of a bushing (chosen randomly) using four different measuring devices.

The three-step research process is summarized in Figure 5. The first stage collected samples, in this case, a bushing from logistics and mold impressions from the bushing' I.D. The second stage obtained I.D measurements of the bushing using a caliper, a dial bore gage, molds and an optical comparator. Mold impressions for I.D were measured using an optical comparator. The final stage of the research produced the results upon which a final determination was made to accept or reject the null hypothesis.

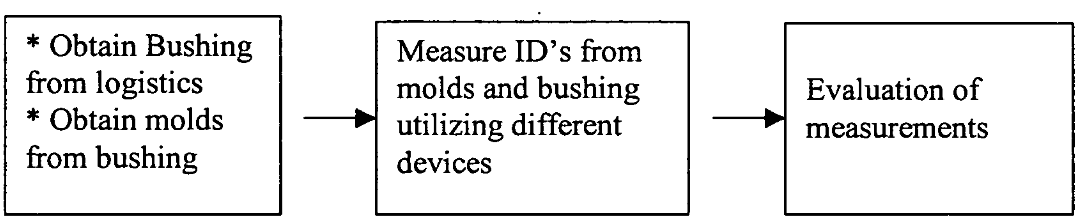

Figure 5. Flow diagram illustrating the three-step research design.

Population

The population was 15 new bushings available from logistics at the Kennedy Space Center, Florida. A non-probability random sampling was used to obtain one desired sample.

Sources of Data

The technical training literature was based on books of measuring techniques, personal experience, Internet documents and basic work procedures for Space Shuttle repair. The raw data consisted of three tables representing the work of the quality technician in three different opportunities. One table contained readings for I.Ds using four different measuring devices. Each reading was subtracted from its nominal value and the difference was then tabled. The variation data were analyzed using the ANOVA file. This file compared the variance of different measuring techniques for I.Ds to the variance of a random sample chosen.

A subject matter expert was consulted in the process completing this project. The expert was certified to read mold impressions using an optical comparator. This special certification is known in the KSC as "CSR".

The Data Gathering Instrument

I.Ds can be measured using direct or indirect devices depending on the size of the part, its location, its shape, etc. A direct method uses a measuring device to display data from a part, i.e. optical comparator; dial bore gage and caliper (see Figures 1, 2 and 3 respectively). An indirect measuring method obtains a duplicate of the part and then this duplicate is measured using direct measurement devices.

The data-gathering instrument in question was the mold impression (indirect measurement device). This material used at the KSC is commercially known as Extrude Medium Reprosil and is the same mold material used for dentists. Extrude Medium features an increased viscosity for higher tear strengths. Its green color is easily distinguishable and its viscosity provides excellent detail for impressions without destructive removal (see Figure 4).

A direct measuring method is preferred over indirect because there is less room for error when intermediate instruments are used. Unfortunately, not all parts are small enough to be brought under an optical comparator or simply cannot be removed from their assembly.

Another measuring device to measure I.Ds is the caliper (see Figure 3). The caliper used in this study had a resolution of 0.0005", accuracy of +/- 0.001", and repeatability of 0.0005".

Dial bore gages were used to measure I.Ds as seen in Figure 2, and are available in convenient sets. Each set consists of a dial indicator, a body and actuating rod, two adjusting wrenches and the probes as specified below. Measurements are taken by comparison so some type of set master should be used as a reference standard.

The split-ball contact is self-centering and the two-point contact makes the gage useful for detecting hole geometry problems like taper, bell-mouth and out-of-roundness. Dial bore reads to .0001", useful for controlling approach to tolerance without removing the sample from its assembly.

Finally, the measuring method used to directly read parts or molds was the optical comparator (see Figure 1). This Nikon vertical beam shadow type comparator has turret

lens of variable magnitude (10X, 20X and 100X power). The quality technician obtains diameters by zeroing out one point in a circumference, then the table is moved across in the X or Y direction and another point of reference is marked. The computer automatically calculates the distance between the two points of reference with X.XXXX" accuracy.

Distribution Method

The data request was distributed by hand to the quality technician on second shift in a Saturday afternoon. The data were collected on the same day later that day by hand. The technician did not stamp the steps of the work request to avoid liability when doing his time card (non-work related). This distribution was convenient for the researcher because the technician's time was a courtesy. In addition, technician' reading accuracy may differ depending upon the day of the week, shift, time, etc. This last statement was not included as an accuracy variation factor because the technician obtained his readings during the same period.

Instrument Reliability

If the study was asked to repeat the same readings two weeks or six months later, the answers probably would not be exactly the same because of the inherent uncertainty generated when human error is involved with tight tolerances. Instead, there is good chance that the readings had similar variances from their nominal value. Readings were expected to be proportional compared to the readings from the first test.

Each measurement device is reliable and its accuracy previously discussed in the Data Gathering Instrument section on page 16.

Instrument Validity

The study focused on test data from processing and tools already employed during the Space Shuttle processing. Personnel taking the readings (quality technicians) have performed this or similar tasks for years besides professional training and school credentials. By employing quality technicians, tools and processes already been performed at KSC, the study insured that the data collected answered the validity of the hypothesis: measuring techniques using caliper, micrometer, dial bore gage and optical comparator are more or equally accurate compared to dental mold technique.

Treatment of the Data and Procedures

To obtain data, a sheet with a table was given to a quality technician. The table requested three trials for each one of the inside diameter readings using four different measuring devices. Once collected, the data were organized in a spreadsheet. A different section in the spreadsheet subtracted each diameter (variation) from its correspondent nominal diameter.

Using a level of significance of 0.05 (high level of confidence), variations from the above step were entered into an ANOVA file to indicate which if any differences are significant (see Figure 6).

To complete the hypothesis test using an F table, the following statistics were necessary:

- Variation table with mean, variance and standard deviation.
- Compute of Sum of Squares Within (SSW), Sum of Squares Among (SSA) and Sum of Squares Total (SST).

- Compute Mean Square Among (MSA), Mean Square Within (MSW) and the value of the F-statistic (F).

	A	B	C	D	E	F	G	H	I
1		Nbr Groups	4		T^2/n	T^2/n	T^2/n	T^2/n	T^2/n
2		Nbr Obs	12		2.293376	2.295125	2.224824	2.296	
3				Column Count	3	3	3	3	
4					Column	Column	Column	Column	Columı
5			Grand Total	10.455	Mean	Mean	Mean	Mean	Mean
6			Grand Mean	0.87	0.874333	0.874667	0.861167	0.874833	#VALU
7					Column	Column	Column	Column	Columı
8	T^2/N	9.11			Total	Total	Total	Total	Total
9	Total T^2/n	9.11			2.623	2.624	2.5835	2.6245	
10	Sq Total	9.11		MSE or	0.8750	0.8750	0.8360	0.8750	
11		SS	df	Variance	0.8755	0.8760	0.8755	0.8745	
12	Between	0.00	3	0.000136	0.8725	0.8730	0.8720	0.8750	
13	Within	0.00	8	0.000121					
14	Total	0.00	11						
15									
16	Level of Significance =		0.01						
17		F =	1.1236						
18									
19		Significant	NO						
20									
21	p=	0.395513863							

Figure 6. ANOVA test for variations of the mean.

Finally, and based on ANOVA test results, accept or reject the hypothesis in terms of the problem.

CHAPTER IV

DISCUSSION OF FINDINGS

Data Collection

The data for this study were collected in the form of work sheets prepared by the researcher. These work sheets represent the measurements of the sample bushing's inner diameter using different devices and performed by a quality technician.

Data Filtering and Analysis

Three trials were taken for each one of the four measuring devices. Molds, optical comparator, dial bore gage and caliper were used to measure the bushings' inside diameter. Measurements required accuracy of ten thousand of an inch. Each measurement represents an attempt to reach the most accurate diameter with the least amount of uncertainty.

The data tables were examined to determine which diameters did not fall within the expected diameters. The filtering did not reduce the number of data points due to considerable deviation.

The first analysis averaged the trials for each measuring device. Simple overview of the data showed that although diameters were taken from the same sample, results may vary when using different instruments. The overview also shows the way measuring techniques can be easily altered when introducing human error.

The second part of the test performs simple analysis of variance (ANOVA) to test the hypothesis that means from four samples (drawn from populations with the same mean). Results will help to validate or reject the hypothesis that dental mold technique is not as accurate or only as accurate as the more traditional techniques. This comparison

will better help understand how the uncertainty can be affected by the way one person reads an instrument compared to another person.

Results for Inside Diameters

Inside diameter results are summarized in Tables 1, 2, 3 and 4.

Table 1

I.D Measurement Using a Caliper

Number of Trials	Inside Diameter Measurement
Trial # 1	0.8750
Trial # 2	0.8755
Trial # 3	0.8725
Average	0.8743

Table 2

ID Measurement Using a Dial Bore Gage

Number of Trials	Inside Diameter Measurement
Trial # 1	0.8750
Trial # 2	0.8760
Trial # 3	0.8730
Average	0.8747

Table 3

I.D Measurement Using Mold Impressions

Number of Trials	Inside Diameter Measurement
Trial # 1	0.8760
Trial # 2	0.8755
Trial # 3	0.8720
Average	0.8612

Table 4

I.D Measurement Using An Optical Comparator

Number of Trials	Inside Diameter Measurement
Trial # 1	0.8750
Trial # 2	0.8745
Trial # 3	0.8750
Average	0.8748

An average was calculated and plotted (Figure 7) to show the results against each other. The red line indicates the linear inside diameter of the bushing while the blue line represents the variance of each method to the nominal inside diameter. The linear diameter (red line) is plotted between the 0.8700" and 0.8750", while the inside diameter

average (blue line) was measured using a caliper, a dial bore gage, mold impressions and an optical comparator. Inside diameter was found in a range of 0.8600" to 0.8750".

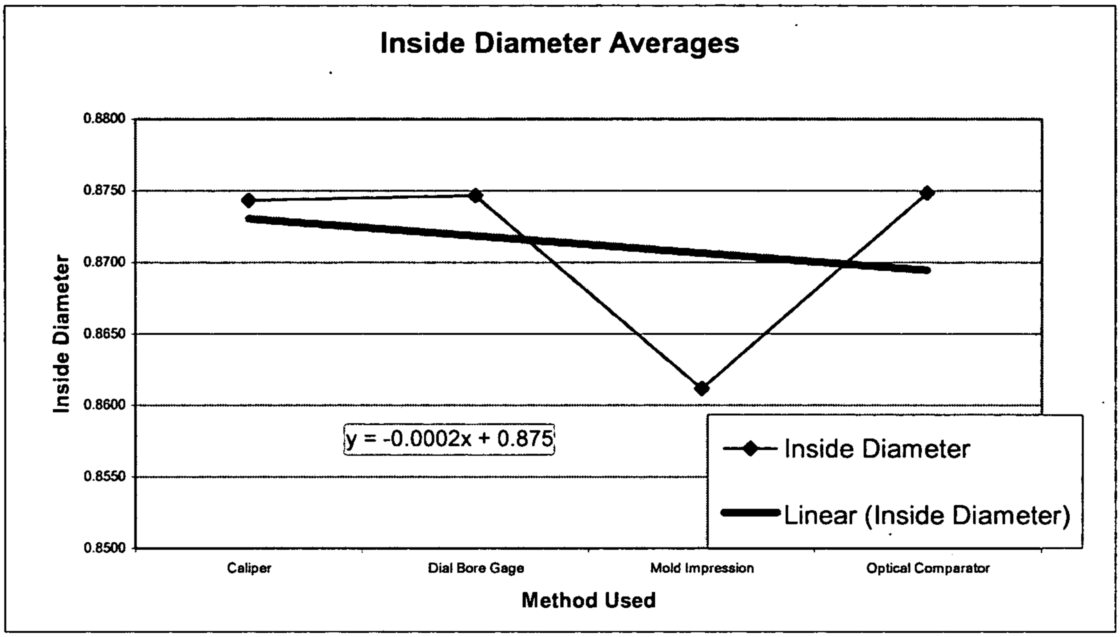

Figure 7. Inside diameter averages.

The total test populations were analyzed using Microsoft Excel statistical analysis software. This analysis yielded the results shown in Table 5.

The research hypothesis stated that the dental mold technique is more accurate than the more direct techniques such as caliper, micrometer, dial bore gage and optical comparator. Hypothesis testing using ANOVA was performed on the diameter measurements. Test concluded that there was not enough evidence to reject the null hypothesis (See Figure 6).

Table 5

Statistical Parameters of Measurements Frequency

Parameter	Caliper	Dial Bore Gage	Mold Impression	Optical Comparator
Mean (x)	0.8743	0.8747	0.8612	0.8748
Variance (S^2)	1.72E-06	1.55E-06	0.0003	5.55E-06
Standard Dev	0.0016	0.0015	0.0218	0.0002

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

This chapter includes the conclusions and final remarks. In the previous chapter, the statistical methods employed support the acceptance of the null. In other words, the mold impressions technique is not more accurate than the more direct techniques used to measure inside diameters such as the use of a caliper, a micrometer, a dial bore gage and/or the use of the optical comparator directly.

Although the utilization of measuring devices and/or techniques are authorized by the systems engineer, sometimes the quality technician gets to choose the most appropriate technique and that is when uncertainty can be compromised if technique is not chosen correctly.

Utilization of the mold impression technique to measure the inside diameter of a bushing with easy accessibility is not recommended. Based on the conclusion driven from the test-analysis, mold impression technique will not work properly or not as accurate when working with tolerances of +0.0000/-0.0005 inches.

If the diameter to be measured has limited accessibility or cannot be removed from the Space Shuttle, then the mold impressions would work best. On the other hand, if measuring devices such as calipers and gages can fit, they are recommended. Such devices will be accurate, fast reading and low cost. If the diameter can be removed to a table, an optical comparator can be recommended.

In conclusion, when measuring a diameter with plenty of accessibility, direct measurement techniques such as gages, micrometers and calipers should be used. Future research can compare accuracy of new devices when they come along.

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